Role of Elastic Anisotropy in Semiconductor Nanopatterning

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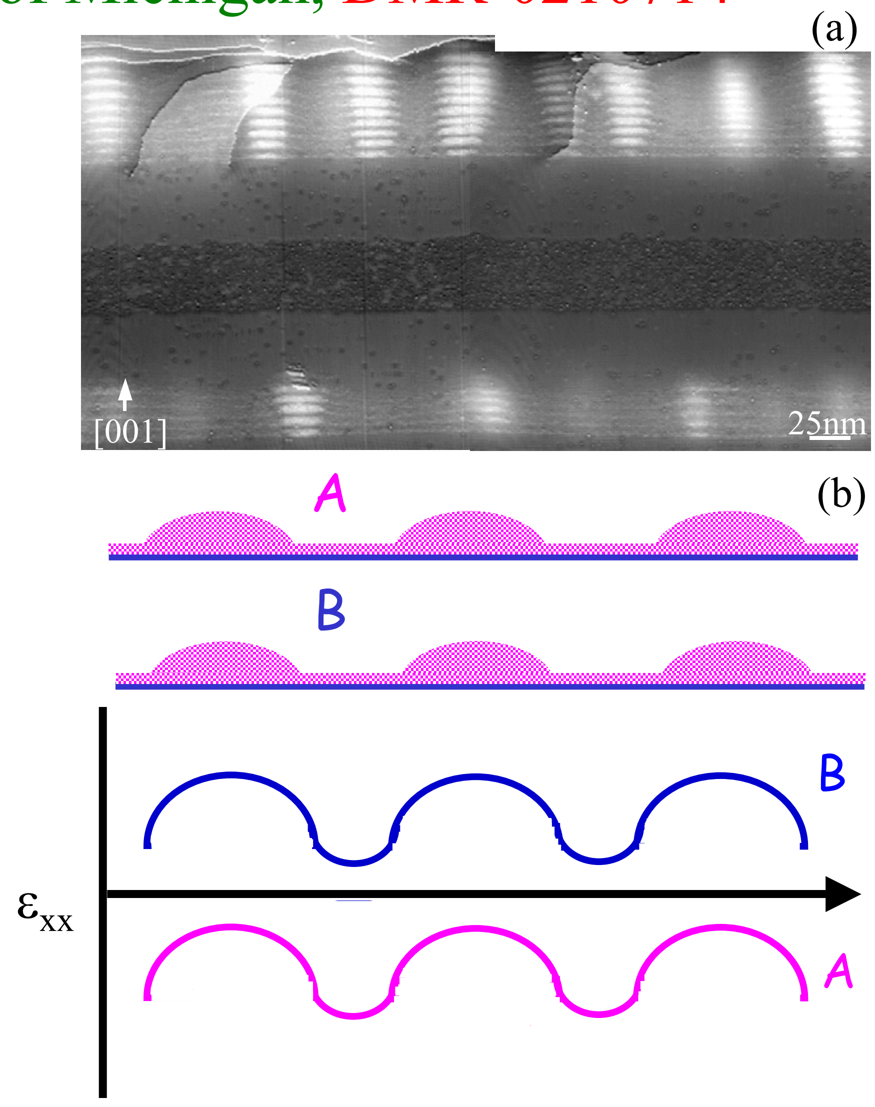
In general, self-assembled quantum dot (QD) formation is driven by the elastic relaxation of stress via island nucleation. The vertical stacking of QDs occurs in a variety of materials systems, such as the InAs/GaAs system shown in (a). Often, this phenomenon is explained by the preferred nucleation of islands at strain energy minima directly above buried islands, as shown in (b). It has been suggested that vertical and lateral correlations between QDs may be controlled by using an elastically anistoropic material for the spacer, layer B. Our work involves investigating possible elastic anisotropies in GaAsN, for use as the spacer layer in InAs/GaAsN QDs.



Semiconductor nanopatterning via self-assembly has shown significant promise for a wide range of electronic and optoelectronic applications. To date, 1D and 2D non-lithographic nanopatterned arrays have been achieved via stacking of self-assembled quantum dot (QD) superlattices (SLs). An example of QD SLs is shown in the cross-sectional scanning tunneling microscopy image in (a). The image shows 5- and 10-period InAs/GaAs QD SLs. Within each layer of QD SLs, bright ellipses of InAs QDs sandwiched between darker layers corresponding to GaAs are apparent. It is evident from the image that the 5- and 10-period QD SLs have organized into columns of vertically correlated InAs QDs. The vertical stacking of QD SLs is often explained by the preferred nucleation of islands at strain energy minima directly above buried islands, as shown in (b). This mechanism predicts the vertical alignment of QDs but does not explain possible lateral correlations. In the case of an elastically anisotropic spacer layer, the strain energy minima often occur at positions laterally offset from an existing island. In that case, island nucleation preferentially occurs at specific *lateral* positions with respect to a buried QD. Thus, in principle, exploitation of elastic anisotropies will provide an opportunity for simple 3D nanopatterning of a wide variety of materials systems.

In this research, we are exploring the role of elastic anisotropy in 3D semiconductor nanopatterning. Specifically, we are examining possible elastic anisotropies in GaAsN for use as the spacer layer in InAs/GaAsN QDs. To this end, ternary GaAsN alloy films with varying alloy composition, lattice misfit, and thickness are grown by Molecular Beam Epitaxy with various in-situ monitoring tools; their elastic anisotropies are measured using Brillouin scattering and interpreted using atomic-scale simulations. Using these alloy films as the spacer material in quantum dot superlattices, the relationship between the elastic anisotropies and the long-range of the order of the resulting quantum dot arrays will then be established. The work established in this project will lay the foundation for a larger effort to develop 3D nanopatterning methods for use in a wide variety of innovative nanostructure devices.

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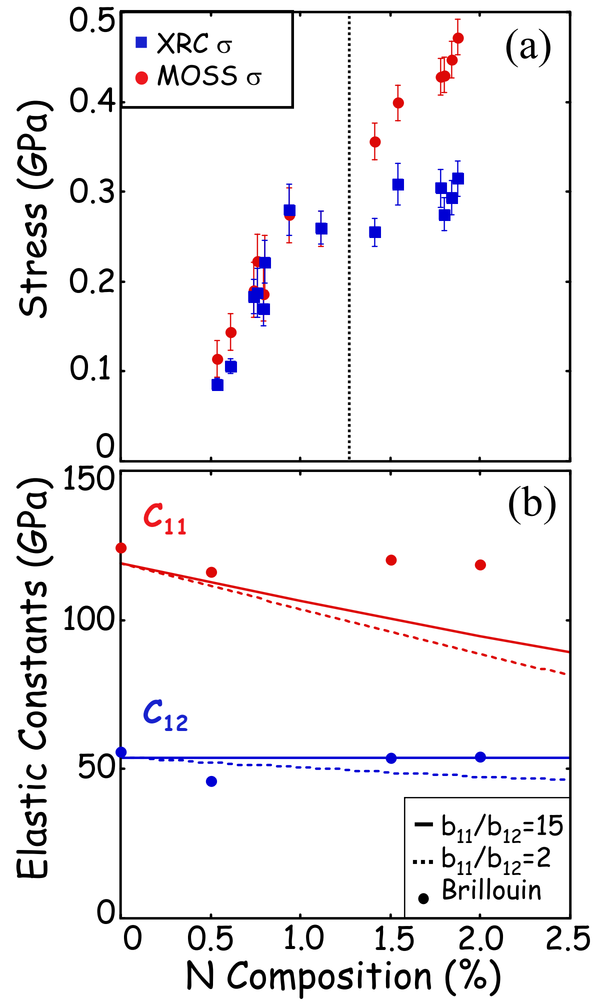
We are exploring the role elastic anisotropy on 3D semiconductor nanopatterning. Recently, we have examined the effects of increasing N composition on the elastic constants and resulting elastic anisotropy in GaAsN alloys for use as spacer layers in quantum dot superlattices. In (a), stresses determined from in-situ wafer curvature measurements ("MOSS σ") deviate significantly from those determined using x-ray rocking curves ("XRC σ"), for compositions >1.3% N. These stress differences are used to determine the elastic constants, which are compared with Brillouin scattering measurements in (b). The observed elastic constant bowing and consequent increase in elastic anisotropy with N composition may be useful for achieving 3D nanopatterned arrays with unique electronic and optical properties.



A comparison of stresses determined using in-situ measurements of wafer curvature (MOSS) with those determined from x-ray rocking curves (XRC) using a linear interpolation of lattice and elastic constants is shown in Fig. (a). In both cases, the composition was independently measured using nuclear reaction analysis. For N compositions > 1.3%, the XRC stresses are higher than the MOSS stresses, presumably due to bowing of the elastic constants in $GaAs_{1-x}N_x$, as follows:

$$C_{ij}(GaAs_{1-x}N_x) = x\ C_{ij}(GaN) + (1-x)\ C_{ij}(GaAs) - b_{ij}\ x\ (1-x)$$

where a linear interpolation (i.e. Vegard's Law) assumes $b_{ij}=0$, and non-zero values of b_{ij} imply bowing of the elastic properties. Figure (b) shows the composition dependence of C_{11} and C_{12} using b_{ij} for which MOSS and XRC stresses are equal, with a range of b_1/b_2 ratios. The composition dependence of the elastic constants is compared with values determined using bulk Brillouin scattering measurements, interpreted using the density and refractive index of GaAs. For more accurate determination of the elastic constants, further surface Brillouin scattering measurements are in progress.

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Education:

11 undergraduates (Ellen Burgunder, Daniel Dettling, Scott Hanson, Molly Hegarty, Rachel Matthews, Blake Nickles, Russell Pong, Nicholas Rudawski, Kai-Hsiung Tsao, Lang Tsui, Tony Wang), 4 graduate students (Vaishno Dasika, Michael Hjelmstad, Matthew Reason, Weifeng Ye), and 2 post-doctoral students (Xiaojun Weng and Liping Huang) contributed to this work. Hanson received the 2004 AVS Undergraduate Student Award. Hjelmstad received the M.S. degree in May 2004. Reason and Ye received Ph.D. candidacy in July and August 2004, respectively.

Outreach:

Several juniors and seniors from high schools throughout North America spent six weeks doing research at UM. The program aims to establish working relationships between H.S. students and active researchers in science-oriented fields and to strengthen and retain student interest in science and engineering careers, especially among students from groups underrepresented in these fields.

Rudawski, Wang, and H.S. student Da Mao, who worked with the Goldman Group during Summer 2004